

WILLIAM WOHLFORT (A)

Design of a Variable Frequency Oscillator

In the fall of 1964, William Wohlfort, a graduate student at Stanford University and a Research Assistant in the Electrical Engineering Department, Stanford Electronics Laboratory, was asked by his supervisor to attempt the design of a variable frequency oscillator. Typically, a research assistant helps with laboratory experiments and analyses related to the research program being conducted by a member of the research staff. At Stanford University, the research assistant may carry nine hours of course work per quarter and spend between 20 and 30 hours per week on paid work in the E.E. Department Laboratory.

Mr. Robert McCoy, the staff member with whom Mr. Wohlfort was to work, was engaged in research involving radar and radar applications. The voltage controlled oscillator which Mr. Wohlfort had been asked to design was to be a part of Mr. McCoy's experimental test equipment. Specifically, the voltage output of the oscillator was to be fed into a quadratic phase or time compression filter. The filter would then be used to enhance the resolution capability of Mr. McCoy's radar equipment.

Since this type of filter was new to Mr. Wohlfort, Mr. McCoy, together with Dr. Bill May and Mr. Robert Miller, spent some time explaining its theory of operation. As the name quadratic phase implies, this filter has a phase characteristic which is proportional to the square of time ($\Phi = k_1 t^2$). Therefore, the time delay of electromagnetic energy in passing through the filter is directly proportional to the frequency of the energy ($f = \frac{d}{dt} = k_2 t$). Theoretically then, if the frequency of the input energy can be varied -- or modulated -- over the bandwidth of the filter and at a rate equal to the filter time delay per unit bandwidth (in this case $1/k_2$), all of the input energy will be directly summed and appear at the output at a given instant of time. This time is determined by the filter's fixed time delay and by k_2 . Dr. May and Mr. McCoy were quick to point out that actual performance was somewhat different from the theoretical. The input energy did tend to sum at the output; however, because of various theoretical reasons as well as construction limitations, it did not sum directly at one instant of time, but rather summed over an interval of time. The peak of the output pulse was, however, much larger in amplitude than the peak of the input pulse.

Mr. Wohlfort performed a series of experiments in the laboratory using a 1 - 2 Mc variable frequency oscillator, the output of which was filtered and fed into a quadratic phase filter. Using a No. 547 Tektronix oscilloscope, he saw that for an input waveform to the quadratic phase filter which approximated a sinusoid being frequency modulated, the output from the same filter appeared as a $\left(\frac{\sin x}{x}\right)$ function with voltage amplitude about 60 times the input peak-to-peak voltage amplitude and with a base width between the first zero crossing about 1/60 the modulation time of the input.

Because of its time compression or summing properties, the quadratic phase filter was being used by Mr. McCoy in his radar research. He explained that a filter at the output of a radar transmitter can be used to sum the average power of the transmitter at a single point in time. Thus, average power may be effectively converted to a large peak power which is necessary for good range performance and a narrow pulsewidth which is necessary for good range resolution of the target.

In the early stages of his experimental work, Mr. McCoy used the previously mentioned variable frequency oscillator which was designed to operate between 1 Mc and 2 Mc. The next step in Mr. McCoy's research program required an oscillator which could be varied over a 10 Mc frequency range. This was the circuit Mr. Wohlfort was asked to design.

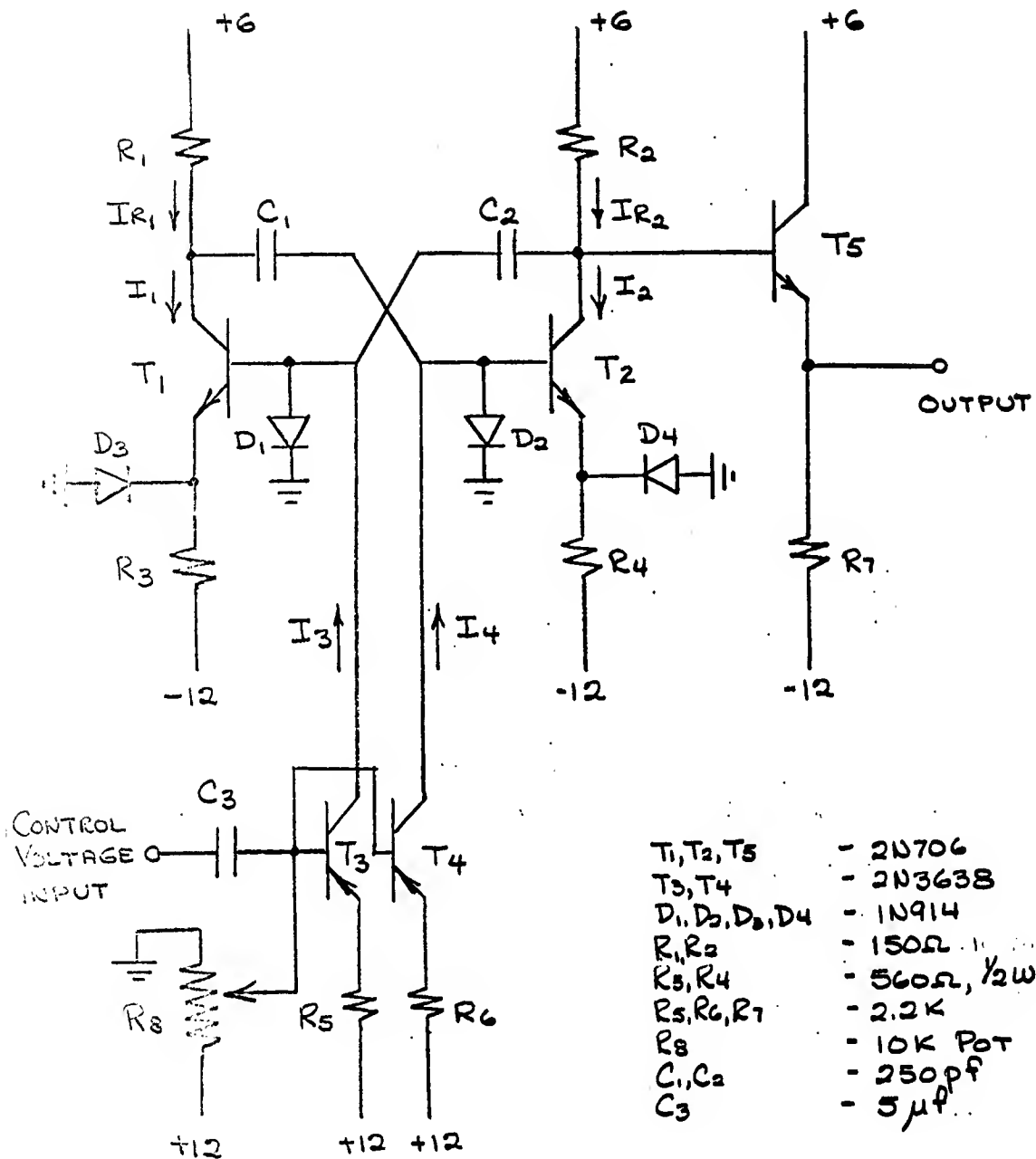
The 1 Mc to 2 Mc oscillator circuit first used by Mr. McCoy is shown in Figure 1. Mr. Wohlfort recognized the basic circuit configuration as being a non-saturating, astable multivibrator or flip-flop. The unique feature of this circuit was that it had two current sources at the bases of the switching transistors. In talking with the designer, Darrell Iverson, Mr. Wohlfort learned that these were constant current sources, used in place of the conventional resistors at the bases, to linearly charge the coupling capacitors, C_1 and C_2 . As Mr. Iverson explained, "By linearly charging the capacitors, the frequency of oscillation is directly proportional to the current source current through the equation $I = \frac{C\Delta V}{\Delta t}$. Since the current source current is directly proportional to the control voltage input to the oscillator, the frequency of oscillation is directly proportional to or a linear function of the control voltage."

Mr. McCoy explained to Mr. Wohlfort that because the quadratic phase filter has a linear time delay versus frequency characteristic, the input frequency to the filter must be modulated in the same linear manner to realize the time compression effect. "It was easiest from the design standpoint," Mr. McCoy continued, "to preserve linearity throughout the system by making the oscillator frequency a linear function of a linear input voltage. The control voltage is the output from a sawtooth voltage generator so there is no need for elaborate matching of the oscillator's transfer function to a special voltage generator to get overall linear frequency control."

In addition to the general 10 Mc frequency range for the new oscillator, Mr. McCoy asked that, if possible, the center frequency be 30 Mc. This would allow him to use existing laboratory equipment, such as i-f amplifiers, which were also centered at 30 Mc. He said that this was not to be an absolute requirement, but one that, if it could be met, would be nice to have. Of greatest importance was the 10 Mc range, linearly controlled by the input voltage.

Mr. McCoy and Mr. Wohlfort also outlined some additional specifications. It was decided that the output voltage amplitude into a 50 Ω load could be anywhere between 0.1 v and 1.0 v. The lower limit was based on noise considerations; the upper limit was more or less arbitrary. The output voltage waveform was to be as symmetrical as possible, both in time and shape. Symmetry was considered important to reduce second harmonic generation which might cause unwanted or spurious filter outputs. It is also necessary for proper performance of the filter that the output voltage amplitude should remain constant over the 10 Mc range.

1 MC TO 2 MC VARIABLE FREQUENCY OSCILLATOR



NOTE: ALL RESISTORS ARE
10%, 1/4 W UNLESS
NOTED OTHERWISE

FIG. 1- (A)

Before coming to Stanford in 1964, Mr. Wohlfort had been employed for five years by IBM in memory circuit design. Therefore, he had considerable experience with switching and amplifier circuit design in the frequency ranges being considered for the oscillator. He suspected that a modification of the present oscillator might be a possible approach since that circuit was of the non-saturating type which he knew was a prerequisite for high-frequency operation. Also, present tuning range of 1 to 2 Mc centered at 1.5 Mc was comparable to 25 to 35 Mc centered at 30 Mc. The upper frequency limit of the present oscillator's basic design did not appear to him to have been reached and the means for linearly controlling frequency by the current source method seemed straightforward. Mr. Wohlfort saw that changing to a variable reactance type circuit was another possibility but one which was not very attractive since he did not have much experience with that type.

In the laboratory Mr. Wohlfort found two Tektronix 585 Oscilloscopes which he could use for most of his work and a Hewlett-Packard 185 Sampling Oscilloscope. Also, there were several power supplies of the Harrison Lab variety, various frequency counters, and two spectrum analyzers. The laboratory had available some of the latest high-frequency semiconductors and there was also the possibility of purchasing transistors and diodes from nearby distributors. He estimated that he could probably get his supervisor's approval to buy \$15.00 to \$20.00 transistors, if necessary, but that a unit costing \$50.00 would be out of the question.

Concerning cost, Mr. Wohlfort concluded that the actual circuit cost was not particularly important since he would be designing only for a single laboratory item; however, cost in the sense of time spent could be important and had to be considered along with the design process.

Although Mr. McCoy had given him no time schedule other than "as soon as possible," Mr. Wohlfort guessed that the design would take between two and four months up to delivery of a fully satisfactory working circuit. Mr. McCoy had noted that he would need only one such circuit. He then added that he had some other work to finish before he could use the new oscillator and, consequently, he would be able to use the 1 - 2 Mc circuit for another three or four months.

WILLIAM WOHLFORT (B)

Design of a Variable Frequency Oscillator

Before attempting the design of a 25 to 35 Mc oscillator, Mr. Wohlfort made an extensive analysis of the 1 - 2 Mc circuit. A cursory look seemed to indicate the possibility of higher frequency performance but he could not be sure to what extent this was true. Furthermore, he expected that the low frequency analysis would permit him to see how predictable the performance, e.g., wave shapes, voltage levels and linearity, would be and how much he could rely upon an analytical extrapolation to the higher frequencies. A low frequency analysis, he felt, would give him some idea as to what design changes were necessary and possible. And, finally, he thought it would be easier and more accurate to make low frequency measurements where test equipment is rather simple and circuit strays are negligible.

Using the 2N706 transistor and 1N914 diode data sheets, but assuming perfect switching in these devices, Mr. Wohlfort made predictions as to what the waveforms would be at the critical points in the circuit. His initial predictions are found in Figure 1. He felt that he could safely assume perfect semiconductor switching, at least initially, since 1 to 2 Mc correspond to 1000 and 500 nsec periods, respectively, and the data sheets indicated the devices should switch in less than 50 nsec.

The collector load resistance and coupling capacitance gave a time constant τ of 37.5 nsec ($150\Omega \times 250$ pf). Thus, when either T_1 or T_2 turned off, he expected its collector would rise at this time constant rate. Furthermore, he expected that the collector voltage amplitude (ΔV_C in Figure 1) would remain constant until a frequency of oscillation was reached where the collectors of T_1 and T_2 did not have enough time to fully recover to their fixed values due to τ . Since in $3\tau = 111.5$ nsec, the collectors should rise to within 5 per cent of their final values in this time. Assuming a 50 nsec turn-on transition, Mr. Wohlfort calculated that ΔV_C would remain essentially constant until approximately: $3 \text{ Mc } 1 \div 2(111.5 + 50) \approx 3 \text{ Mc}$. Therefore, based on the requirement that the oscillator output voltage should remain constant in amplitude for its application with the quadratic phase filter, he concluded that the oscillator would certainly meet that requirement in the 1 - 2 Mc range and should be adequate up to 3 Mc.

In considering the linearity of the low frequency oscillator, Mr. Wohlfort first assumed that $\Delta V_C = \Delta V_B$, i.e., the entire collector voltage transition would be coupled across the capacitor to the base of the opposite transistor. In doing so he neglected stray capacitance at the transistor bases since he regarded it as negligible compared to the 250 pf coupling capacitor. He also neglected any charging of the coupling capacitor during the negative transition at the base. Therefore, using the formula $I = C \frac{dv}{dt}$

THEORETICAL WAVEFORMS AT 2 MC

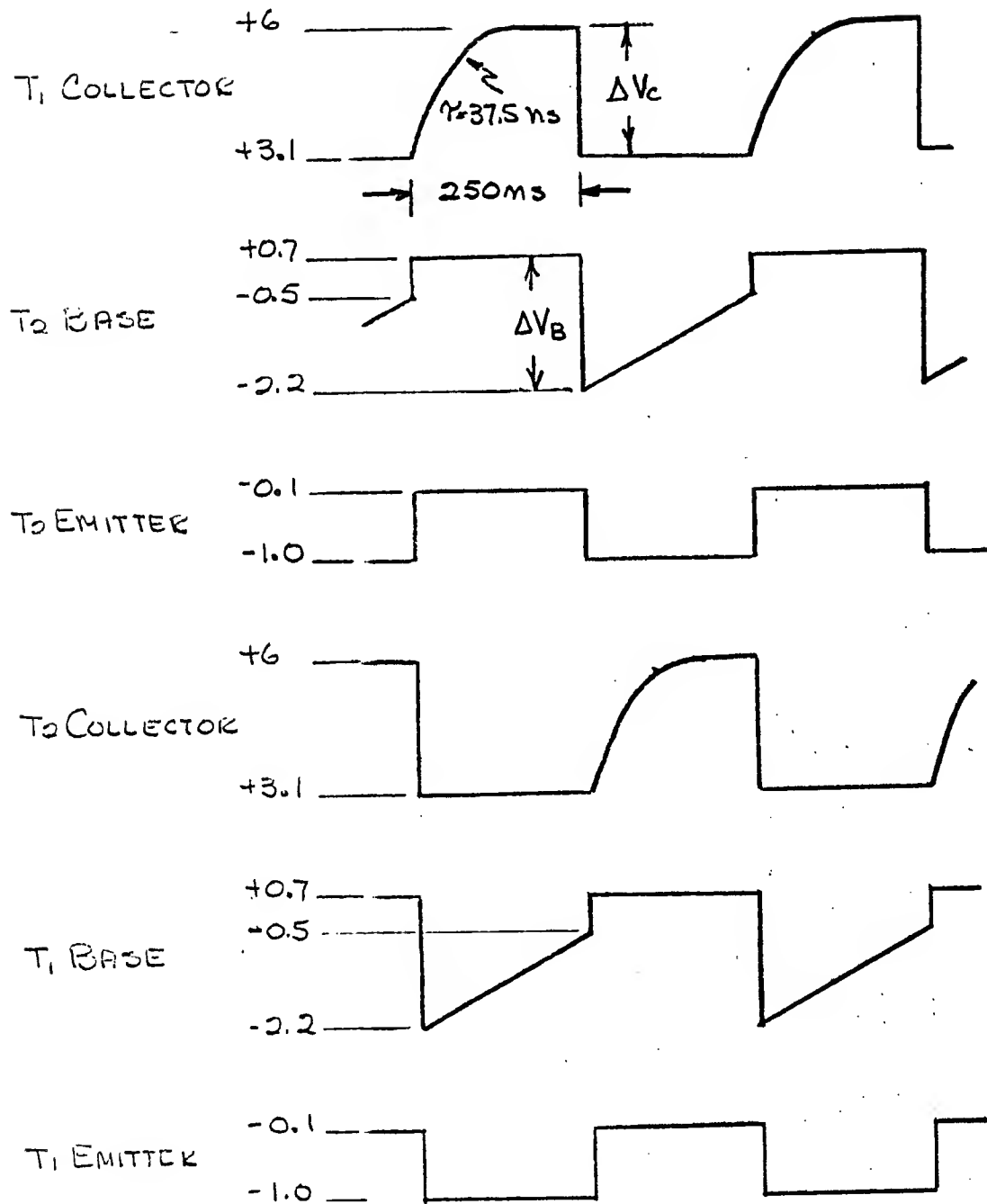


FIG 1.- (B)

he obtained the relationship:

$$I_3 = C_2 \left[\frac{\Delta V_b}{\Delta t} \right] = C_2 \left[\frac{\Delta V_c}{\Delta t} \right]$$

now for $\Delta t = \frac{T}{2} = \frac{1}{2f}$

where f = frequency of oscillation

$$f = \left[\frac{1}{2C_2 (\Delta V_c - 1.2)} \right] I_3$$

Now ΔV_c may be expressed by

$$\Delta V_c = I_2 R_2 \left[1 - \exp \left(- \frac{T}{2\tau} \right) \right]$$

where: $I_2 = \frac{12 - V_{D4}}{R_4}$; $V_{D4} = 1.0V$

where T = period of oscillation

Therefore:

$$f = \frac{1}{2C_2 \left(I_2 R_2 \left[1 - \exp \left(- \frac{T}{2\tau} \right) \right] - 1.2 \right)} I_3$$

at low frequencies (less than 3 Mc)

$$T \gg 2\tau \text{ and } \exp \left(- \frac{T}{2\tau} \right) = 0$$

Therefore, for $f < 3 \text{ Mc}$

$$f = KI_3$$

$$\text{where } K = \frac{1}{2C_2 (I_2 R_2 - 1.2)}$$

From this analysis Mr. Wohlfort concluded that the oscillator should have a linear frequency vs. current source current characteristic, and, therefore, a linear frequency vs. control voltage characteristic below 3 Mc. A plot of his predicted frequency vs. control current function is found in Figure 2.

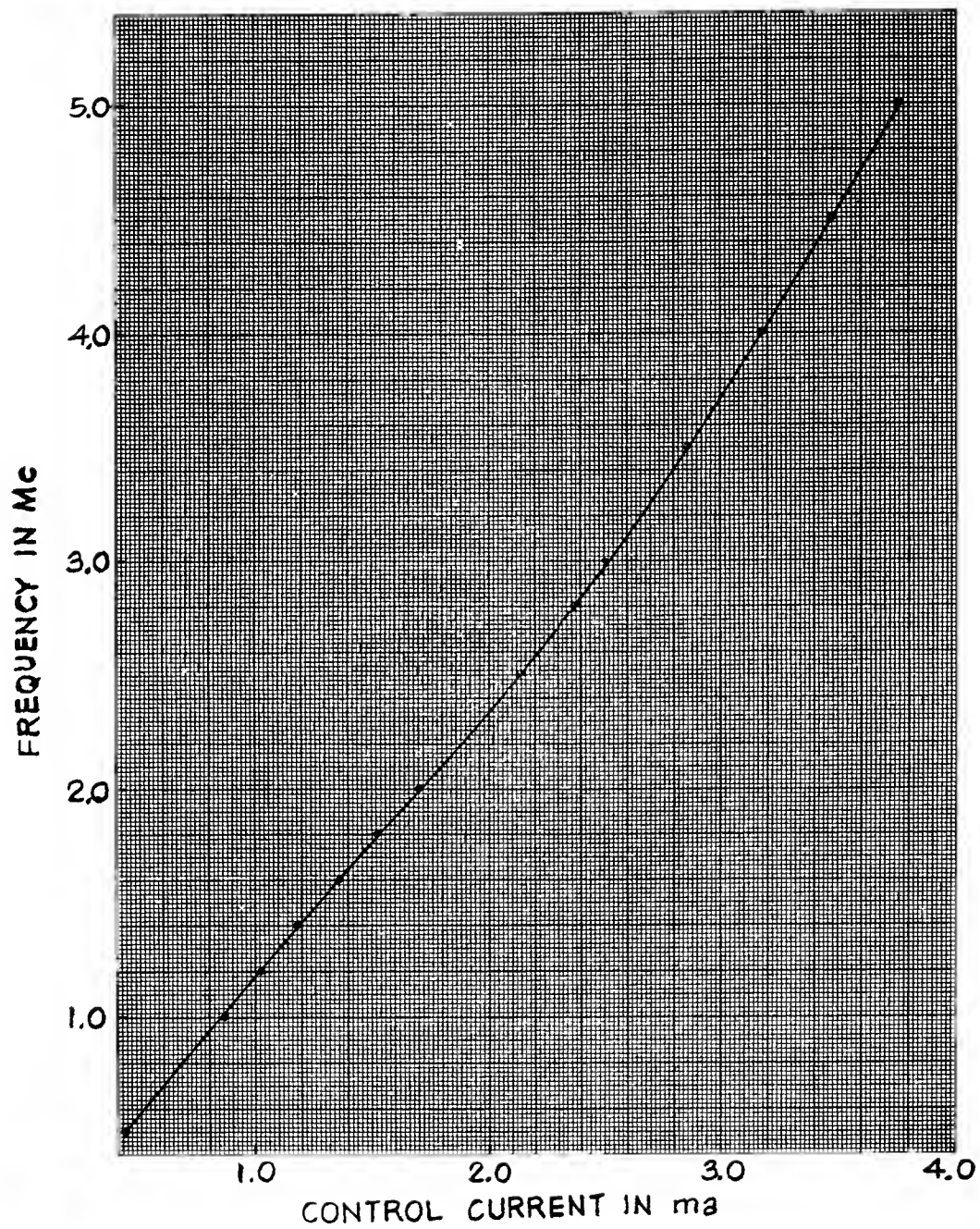


FIG. 2 - (B)
PREDICTED FREQUENCY VS CONTROL CURRENT

In the laboratory, Mr. Wohlfort performed a series of experiments and tests on the oscillator to check his analytical assumptions. To observe the waveforms, he used a Tektronix 547 Oscilloscope with Type CA dual-trace plug-in amplifier. An Electronic Counter, Hewlett-Packard 5245L, was used to measure frequency and a Fluke Differential Voltmeter was used to measure the control voltage as it was varied by the potentiometer.

Mr. Wohlfort found the critical voltage wave shapes and amplitudes to be in general agreement with his predictions. The measured and predicted wave shapes are compared in Figure 3. The main difference was in the finite turn-on or fall-time, which was about 30 nsec measured in the circuit. As he had also predicted, the collector circuits of the switching transistors appeared to have a time constant near the calculated value of 37.5 nsec.

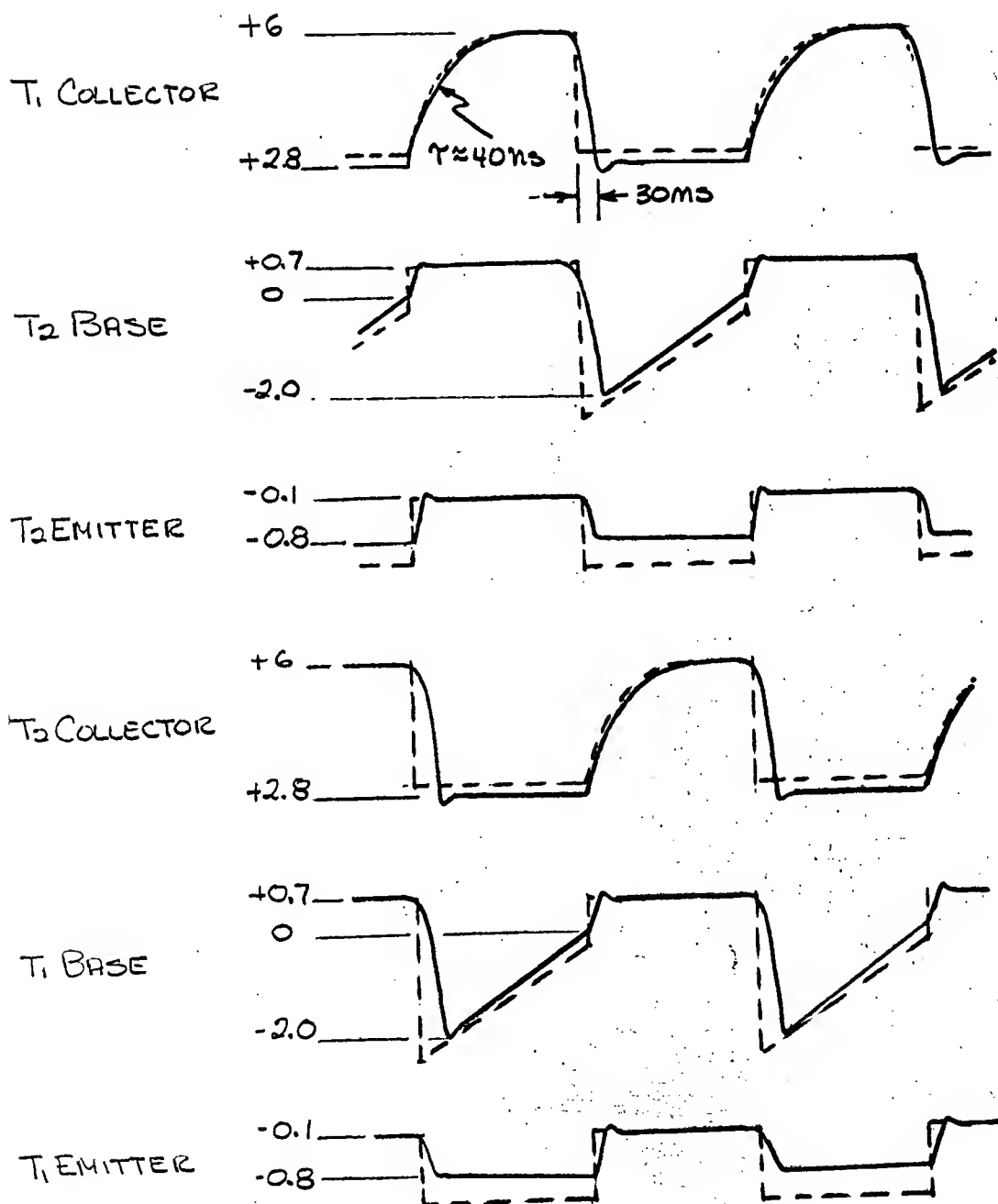
However, when Mr. Wohlfort made a plot of output frequency vs. control current, Figure 4, he noticed that instead of being linear up to 3 Mc, there was a definite rounding of the curve starting at 2.5 Mc. At first he did not know whether the rounding was due to experimental error, to an error in his assumptions, or to some other circuit behavior which he had overlooked. A recheck of a few of the plotted points convinced him that experimental error was not the cause of the discrepancy. A review of his calculations showed no apparent errors. Probably, Mr. Wohlfort thought, he had overlooked something in the operation of the circuit.

From his initial calculations he knew that the circuit would become non-linear as ΔV_B decreased. Theoretically ΔV_B should not decrease until ΔV_C began to decrease due to insufficient time to recover the collectors of the switching transistors, i.e., at around 3 Mc. Therefore, Mr. Wohlfort decided to look first at the base wave forms to see if ΔV_B began to decrease at frequencies below 3 Mc.

In the laboratory he was surprised to see ΔV_B decreasing, not merely below 3 Mc, but in a somewhat linear fashion through the range from 500 KC to 3 Mc and beyond. Actually, he did notice that his decrease in ΔV_B became more rapid above 2.5 Mc. At 3 Mc and beyond ΔV_B decreased even more rapidly. This, Mr. Wohlfort assumed, was due to the collector time constant effect.

Since ΔV_B was related to ΔV_C , he next looked at the collector voltage of the switching transistors. In agreement with the decrease in ΔV_B from 500 KC to 3 Mc was a decrease in ΔV_C over the same range. After observing the decrease in ΔV_C below the range where time constant is important, the reason for the decrease became obvious to Mr. Wohlfort. A decrease in ΔV_C meant a decrease I_{R_2} , the current through R_2 , the 150 Ω collector load resistance. Assuming the switching transistors to be current sources, then I_2 must be constant. A decrease in I_{R_2} then must

THEORETICAL AND MEASURED WAVEFORMS AT 2 MC



— MEASURED
--- THEORETICAL

FIG. 3-(B)

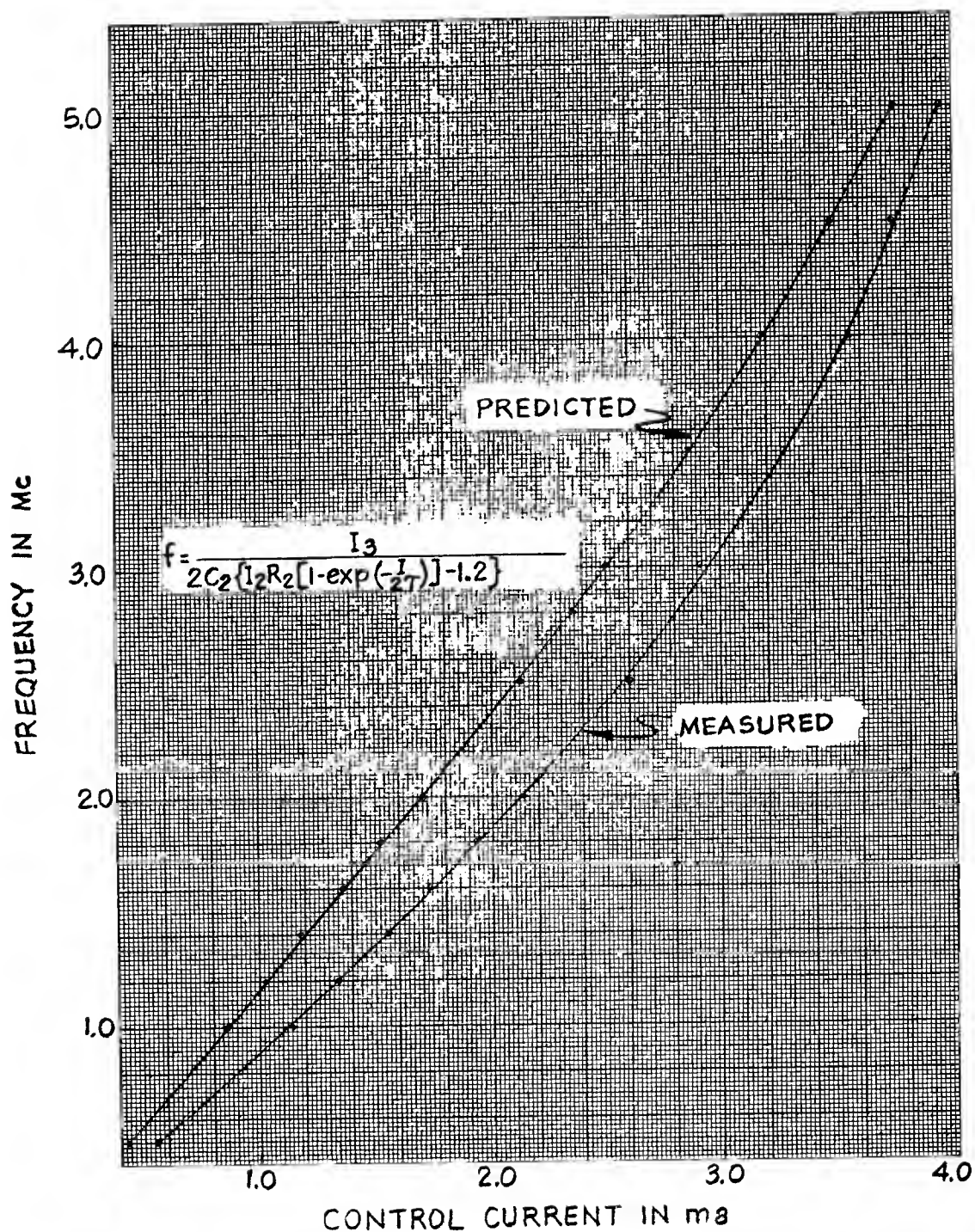


FIG. 4 - (B)
PREDICTED AND MEASURED
FREQUENCY VS CONTROL CURRENT

correspond to an increase in current through C_2 . But this is precisely the increase in control current I_3 . Therefore, Mr. Wohlfort concluded, the decrease in ΔV_C from 500 KC to 3 Mc. was due to the increase in control currents I_3 and I_4 over that range, causing an identical decrease in I_{RL} .

Mr. Wohlfort then modified his original equations to include this effect. In addition, he made several other changes to include the finite transistor time, recorded diode drops, and recorded current and voltage levels.

In place of I_2 , he used R_2

$$I_{R_2} = I_2 - I_3$$

For $I_2 R_2$, he used 3.3 v

For V_{D4} , he used 0.8 v

$$\text{For } = C \frac{dv}{dt}, \text{ he used } I_3 = C_2 \left[\frac{\Delta V_C - 0.7}{\Delta t} \right]$$

$$\text{For } \exp\left(-\frac{T}{2\tau}\right), \text{ he used } \exp\left(-\frac{T - 60}{2\tau}\right)$$

then

$$f = \frac{1}{2C_2 (I_2 - I_3) R_2 \left[1 - \exp\left(-\frac{T - 60}{2\tau}\right) \right] - 0.7} I_3$$

He then plotted the new relationship for frequency vs. control current, Figure 5, and found it to be in close agreement with the measured results.

Mr. Wohlfort concluded he was ready to begin the 25 to 35 Mc design. At 1 - 2 Mc the oscillator had performed as predicted. Those initial discrepancies between prediction and performance had been resolved and incorporated into a new set of analysis functions which closely described actual performance. Because performance was predictable and because there were no immediately obvious limitations, Mr. Wohlfort felt he could design a higher frequency version. However, he was not sure he could reach 35 Mc. He knew that circuit strays, fall-times, and time constants would be much more important but he didn't know how far he could go in minimizing them.

As a first step in getting to higher frequencies, Mr. Wohlfort thought he might look for a higher speed transistor with which to get faster switching action. He also thought that the reduction of the coupling capacitance and switching transistor load resistors together with the increase of switching transistor current would be possible ways to increase the upper frequency limit of the oscillator

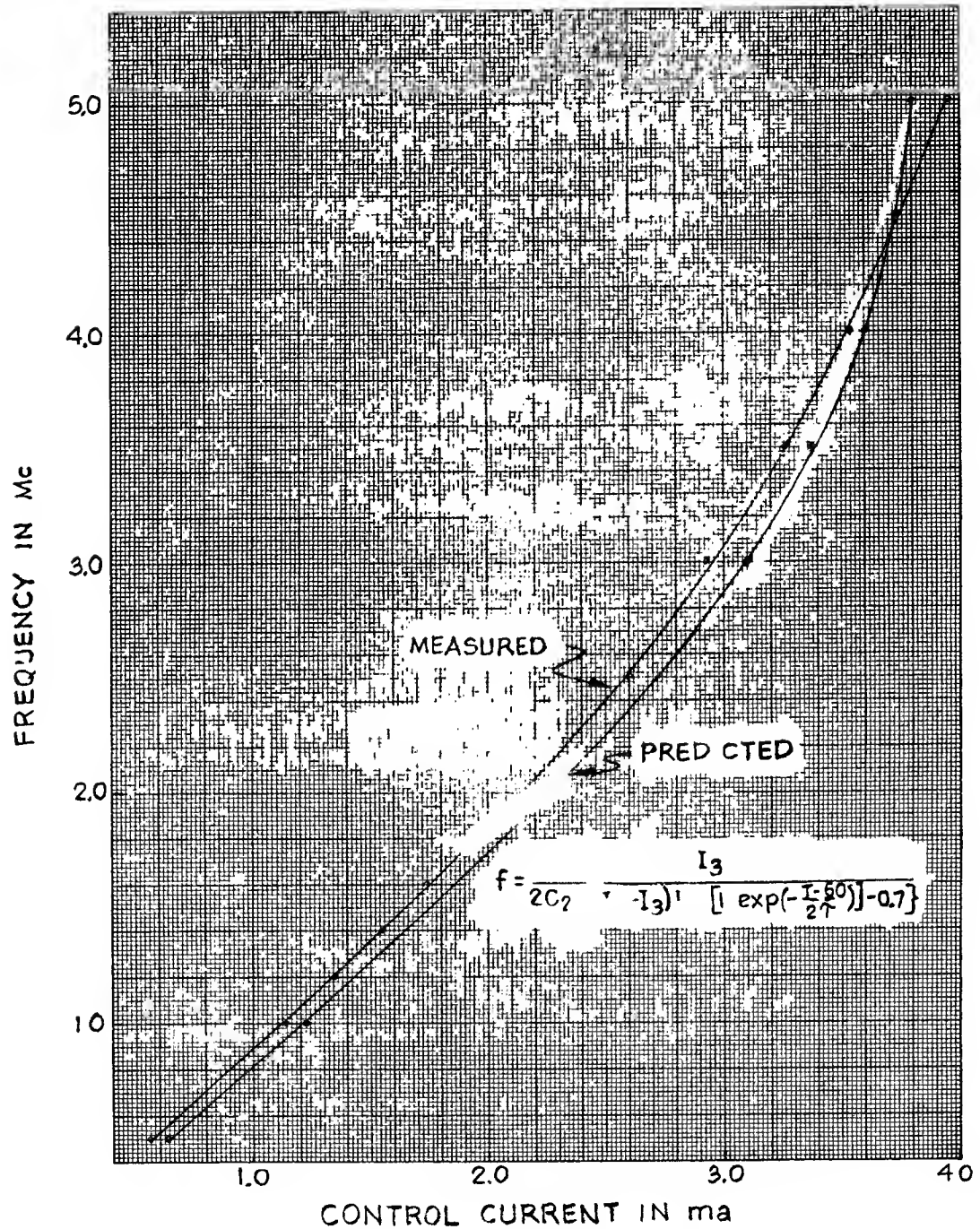


FIG. 5 - (B)
PREDICTED AND MEASURED
FREQUENCY VS CONTROL CURRENT

WILLIAM WOHLFORT (C)

Design of a Variable Frequency Oscillator

In approaching the design of a 25 to 35 Mc oscillator, which was to be linearly voltage controlled and have a constant amplitude, symmetrical output, Mr. Wohlfort considered his first task to be that of getting a circuit which would at least oscillate in the desired frequency range. Regardless of the linearity and waveshape requirements, he believed he first needed an operating circuit.

Mr. Wohlfort made the component changes which he proposed after studying the 1 to 2 Mc circuit. To replace the 2N706 transistor he found he would have to purchase units from a vendor since the E. E. stockroom did not carry units of higher frequency response - f_t - than the 2N706. He first selected the 2N918. However, these transistors at the time cost \$15 each.

Not knowing whether he would be successful in his design, Mr. Wohlfort decided to purchase the 2N2475 transistor at \$5.00 each as initial 2N706 replacements. The f_t of the 2N2475 (750 Mc) was not quite as high as that of the 2N918 (900 Mc) but was higher than that of the 2N706 (400 Mc). As such, if a frequency improvement was available in the circuit design, Mr. Wohlfort expected to see it.

To reduce capacitance at the base of the switching transistors he replaced the 2N3638 transistors with 2N3640 units which were in stock. The 1N914 was the highest frequency diode the E.E. stockroom had. Not being sure from earlier tests that they should be replaced, he left them in the circuit.

In calculating a value for the coupling capacitor Mr. Wohlfort considered stray capacitance at the bases of the switching transistors, collector time constant and charging current. Estimating stray capacitance to be on the order of 8 to 10 pf, - by consulting the 2N2475 and 2N3640 transistor data sheets and the 1N914 diode data sheet, - he tentatively chose 15 pf as the minimum to which the coupling capacitor could be reduced. Calculating the collector time constant τ he found this to be 2.25 nsec with the original 150 Ω load resistor. He considered reducing the 150 Ω but knew that because of the voltage division which would occur across the 15 pf coupling capacitor and the 8 to 10 pf of stray capacitance, the voltage transition at the base of the switching transistor would already be considerably reduced. Mr. Wohlfort noted from the 2N2475 and 2N918 data sheets that he could not expect optimum transistor switching performance if currents in these units greatly exceeded 20 MA. Thus, he could not consider reducing the 150 Ω resistors while increasing transistor current to retain the same collector voltage swing..

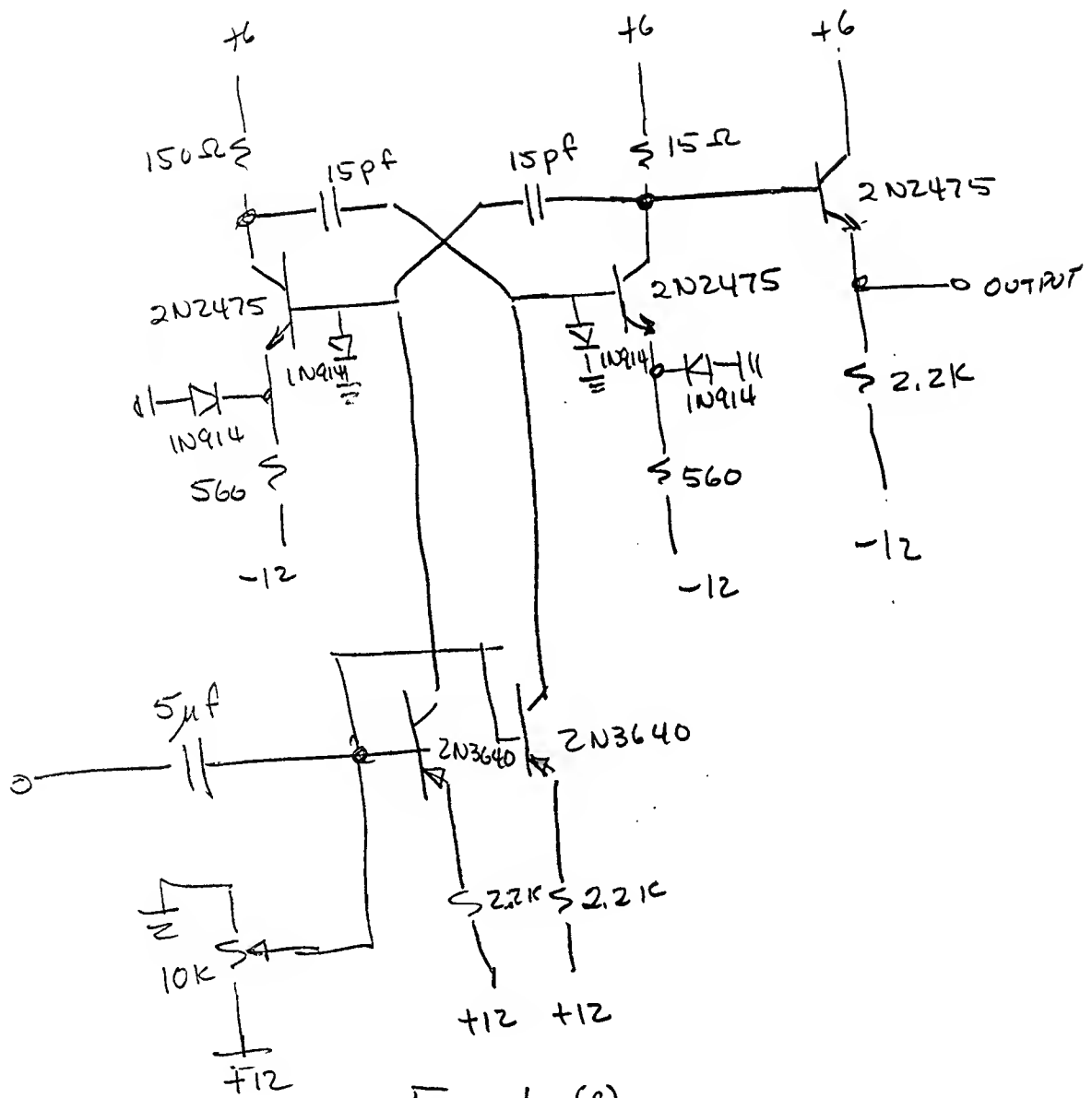


FIG 1-(c).

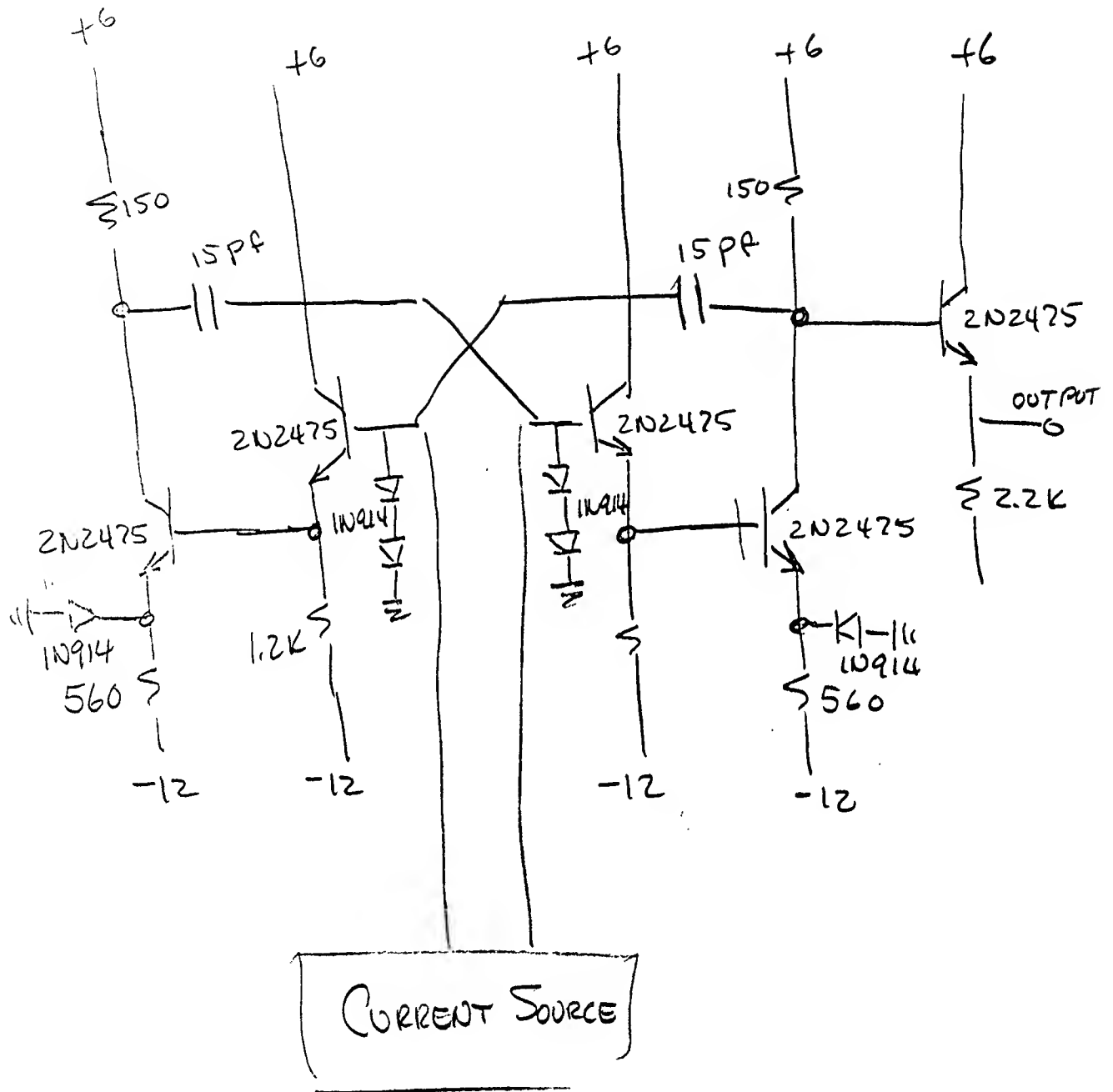


FIG 2-(c)

To keep the circuit symmetrical he decided to replace both diodes with transistors, allowing two output points. Figure 3 shows these modifications.

In the laboratory Mr. Wohlfort was able to get this circuit to oscillate to 40 Mc, although somewhat unstable, using 2N2475 units as the common base transistors. The circuit appeared sensitive to environment. In particular, capacitance changes due to movement or location of the hands or body changed the frequency of oscillation noticeably. Expecting that he could achieve more stable performance with the 2N918 transistor and thus get a more solid design in the 25 to 35 Mc range, Mr. Wohlfort obtained his supervisor's permission to buy six units. To reduce capacitance to a minimum and guarantee fast diode switching, he also purchased FD 700 diodes to replace the 1N914 units. When these new components were added to the circuit, there was no noticeable improvement. This was rather disappointing in view of the additional cost, but indicated to Mr. Wohlfort that the circuit configuration and perhaps even its basic design was now the limiting factor rather than individual components.

Concentrating for a moment on the shape of the output pulse at the collector of the current mode switch, Mr. Wohlfort saw that the pulse was not symmetrical about its average value. This could be expected, he reasoned, since he was looking at rise and fall times and on and off levels which were not necessarily the same. However, he thought, if the output could be taken differentially across both collector loads then the waveshape would be much more symmetrical. From another student in the laboratory he obtained an N.H.E. 0501BB Wide-Band Transformer with a 300Ω primary impedance and a 50Ω secondary impedance. This he attached directly across the 150° load resistors, Figure 4, and so obtained symmetrical (about the average value) wave shapes. In addition, he had also succeeded in referencing the output signal to ground which would simplify connecting into the quadratic-phase filter.

Now that he had a circuit which was operating in the desired frequency range and from which he could expect to get an output without excessive loading, Mr. Wohlfort started to take data on frequency vs. control current. For these measurements he again used the Fluke Differential Voltmeter to measure the voltage across the 2.2 K current source resistors and the H.P. 5245L Electronic Counter. This data, which measures only the output frequency and not its amplitude, is contained in Figures 5 - 7.

After rechecking a few points to convince himself that the data was accurate, Mr. Wohlfort immediately saw that the output frequency vs. control current was not linear in the desired 25 to 35 Mc region. In fact, the data clearly showed that the circuit began to depart from linearity in the region between 20 and 25 Mc and became progressively non-linear with increasing frequency.

ECL-35 (C)

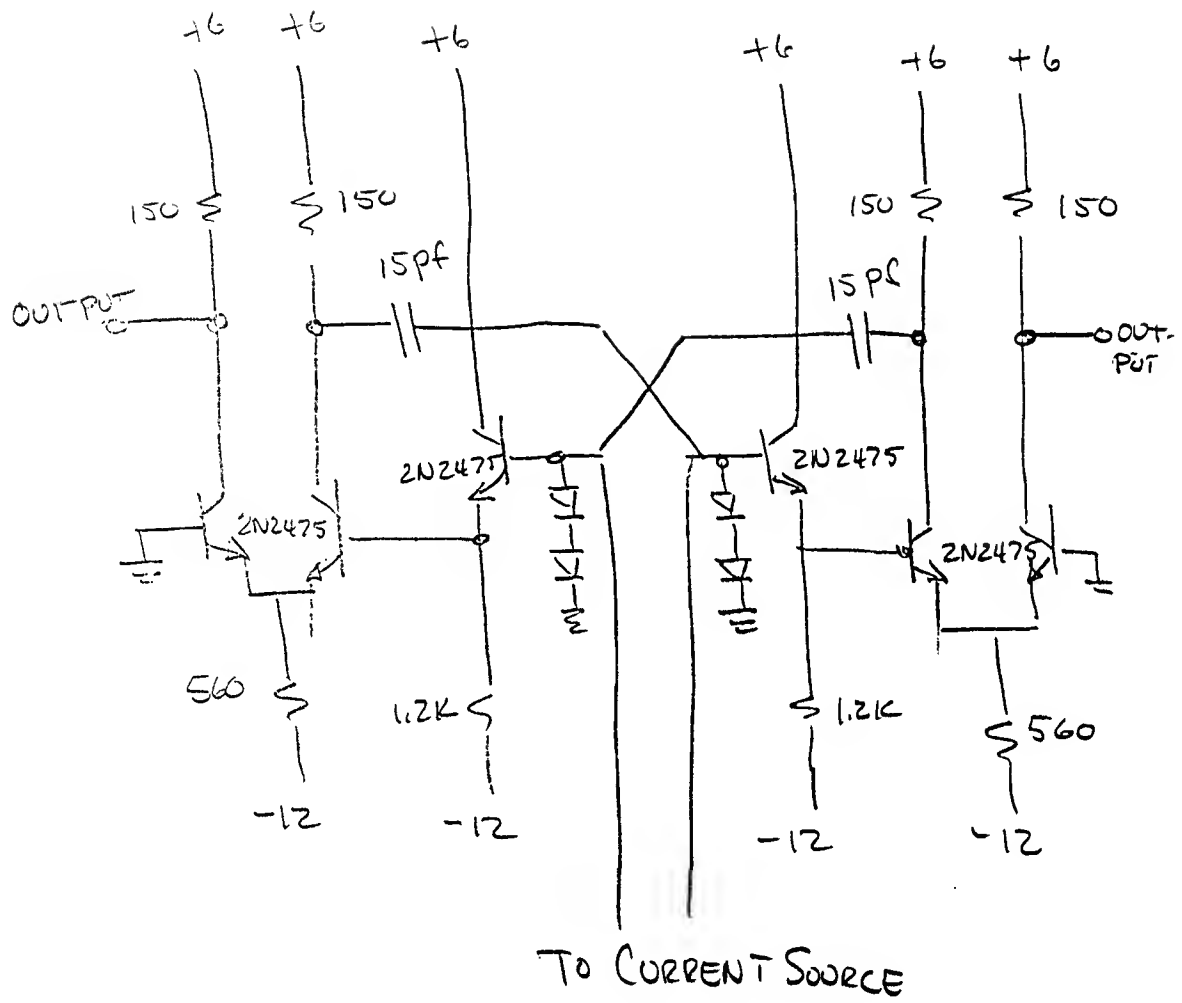


FIG 3.- (c)

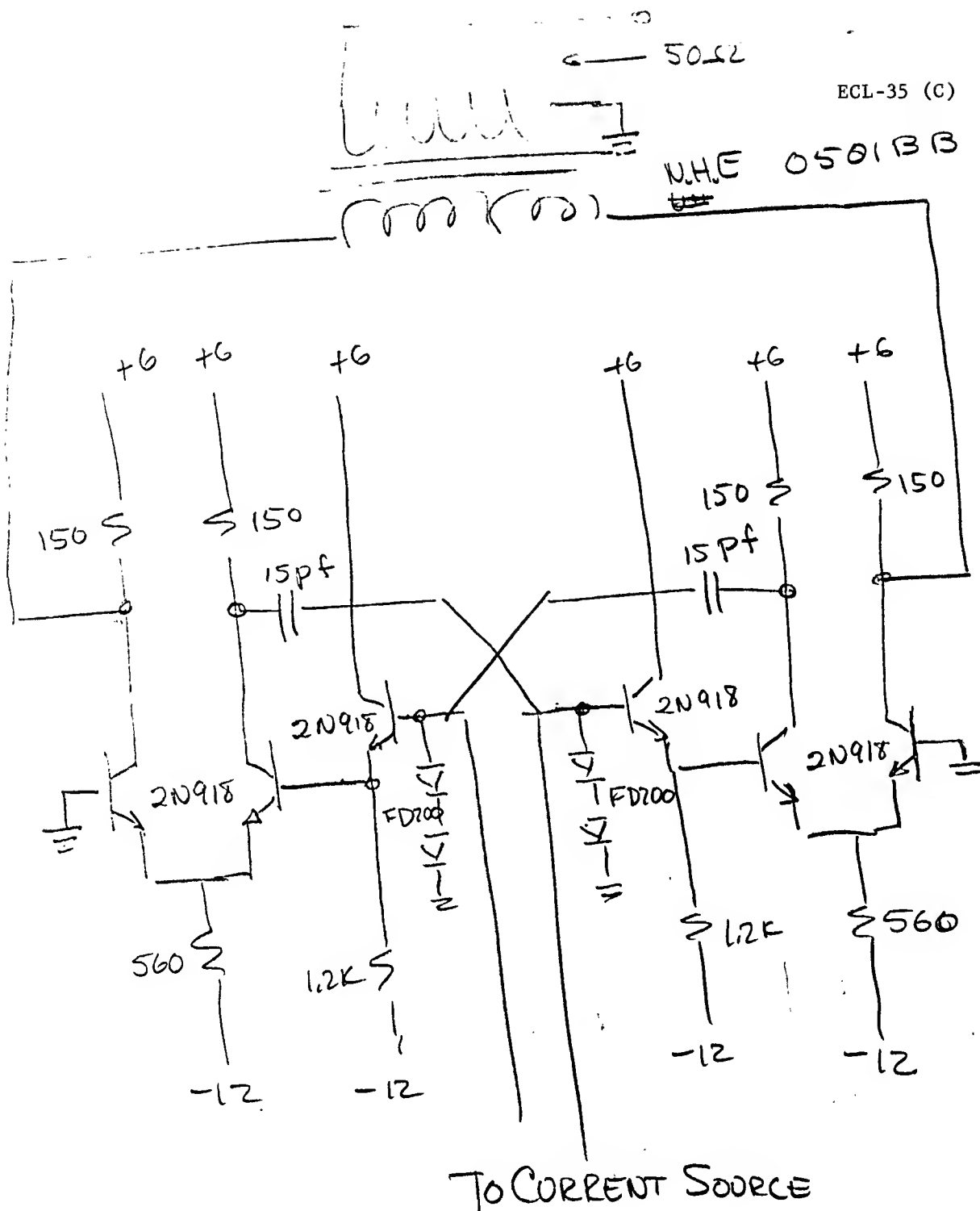


FIG. 4-(c)

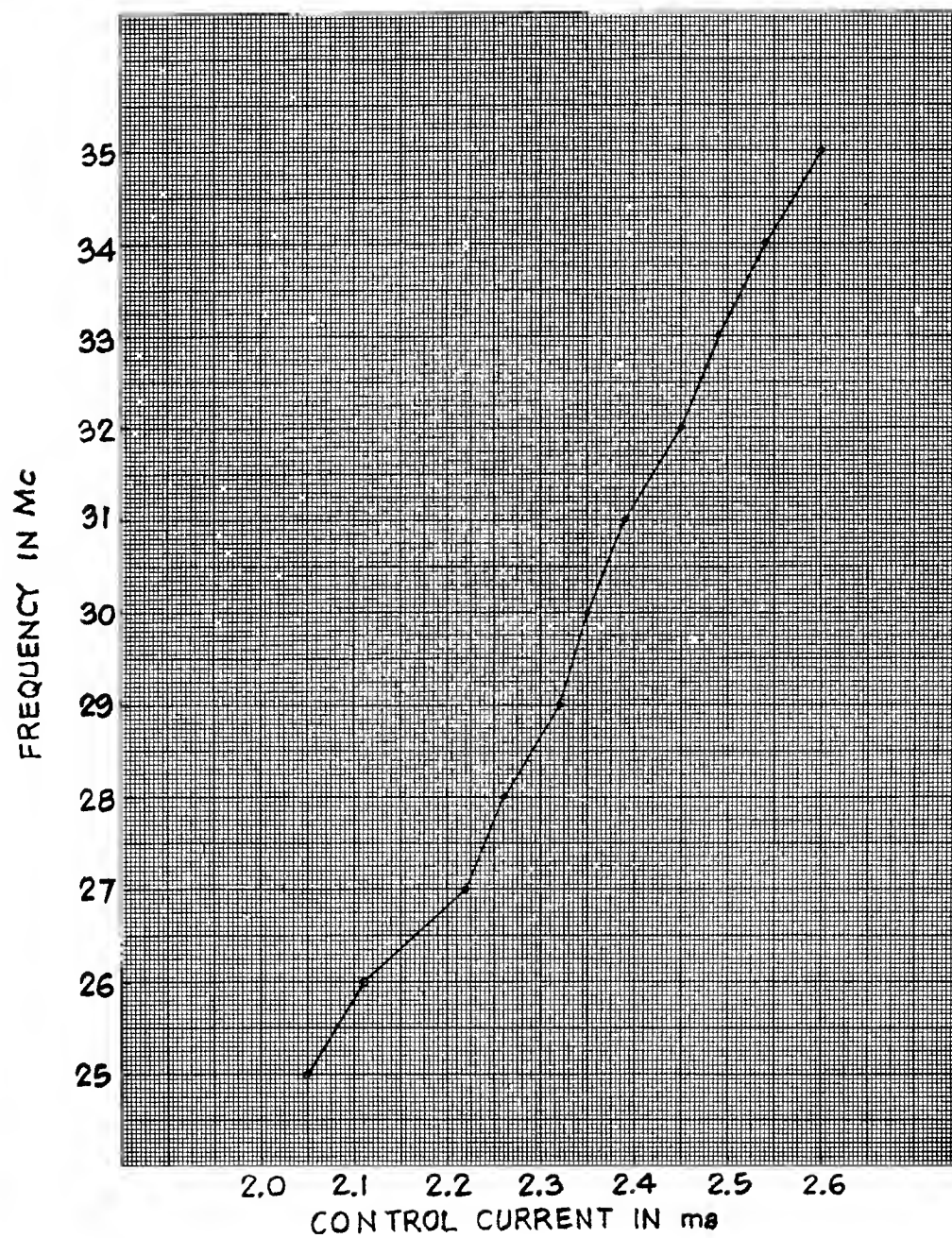


FIG. 5 - (c)
FREQUENCY VS CONTROL CURRENT
25Mc TO 35Mc

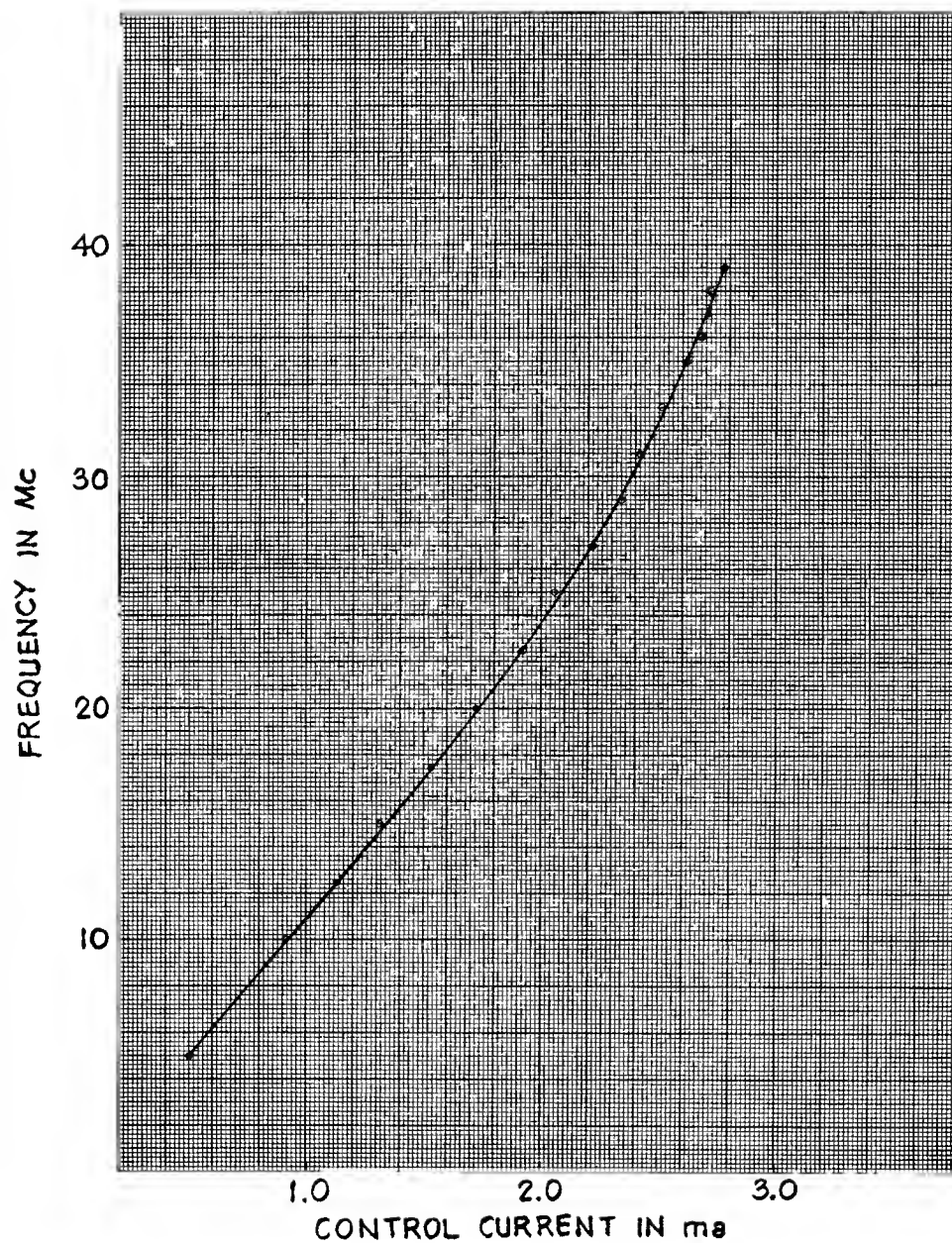


FIG. 6 - (c)
FREQUENCY VS CONTROL CURRENT
5Mc TO 39Mc

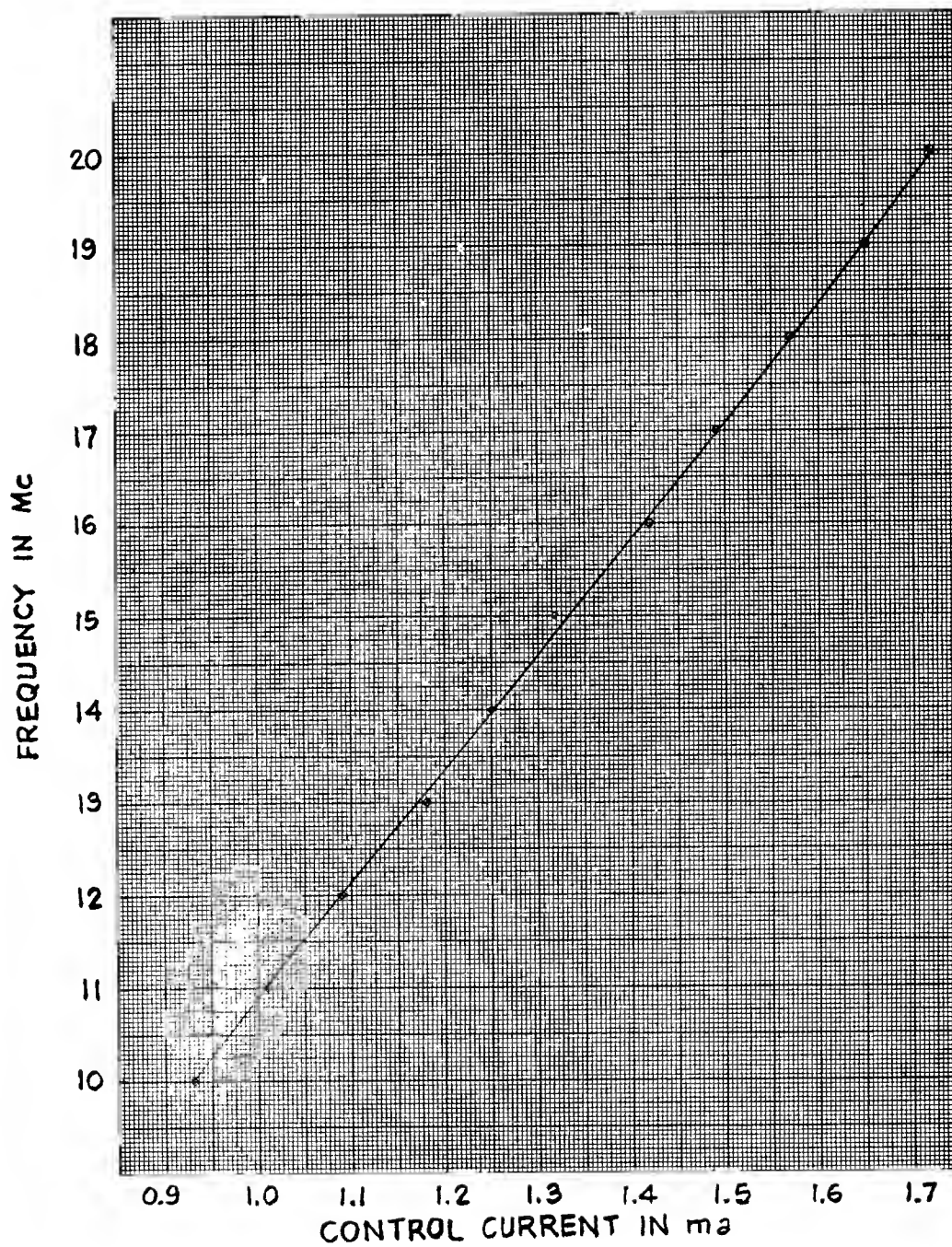


FIG.7- (C)
FREQUENCY VS CONTROL CURRENT
10Mc TO 20Mc

A check of the circuit using the 581 Oscilloscope with Type 80 plug-in and cathode-follower probe showed Mr. Wohlfort that, as in the 1 to 2 Mc circuit, non-linearity was due to a decrease in the voltage transition at the base of the switching transistors. At the lower frequencies he had postulated that this decrease could be due to (a) decrease in collector voltage transition due to insufficient recovery time, (b) decrease in collector voltage transition due to increase in control current, and (c) charging of the coupling capacitor during the negative transition period. He decided that (a) was not the cause of non-linearity in the 20 - 30 Mc range since τ was sufficiently small so as to allow full recovery in the periods corresponding to those frequencies. Furthermore (b) should not be a major cause of non-linearity in the 20 to 35 Mc range since with the reduction of the coupling capacitor from 250 pf to 15 pf the control current was still approximately the same as at low frequencies and he had observed no major non-linearity in the 1 to 2 Mc operating range.

However, Mr. Wohlfort realized that (c) could be a major cause of non-linearity. This he deduced when he considered that the negative transition time of approximately 8 nsec was quite comparable to the positive coupling capacitor charging times which range from approximately 17 to 6 nsec in the frequency range 20 to 35 Mc.

The only solution Mr. Wohlfort could suggest was that the fall time transition be decreased from 8 nsec to something on the order of 2 nsec. But this he knew was impossible for the existing circuit since, as he had experienced, faster transistors did not appear to improve performance above a certain range, so that he concluded performance to be design limited.

Therefore, to get linear operation from 25 to 35 Mc, Mr. Wohlfort concluded that a new design approach was required.

At this point his supervisor, Dr. May, suggested that it might be possible to run the circuit at a center frequency of 10 Mc and, running the oscillator into a 25 to 35 Mc bandpass filter, use the third harmonic component of the oscillator output signal. The idea seemed good to Mr. Wohlfort because, as his data showed, the circuit was linear below 20 Mc so he could expect the third harmonic around 10 Mc to be linear. Furthermore, it would permit him to increase the value of the coupling capacitor above 15 pf and make other modifications which would allow the circuit to be even more stable at the lower operating frequency.

Using a Spectrum Analyzer Mr. Wohlfort investigated the third harmonic characteristics of the oscillator output. Since the output was square-wave-shaped, he expected that even harmonics would be considerably smaller than odd harmonics. He operated the oscillator between 8 and 12 Mc to get the third harmonic range of 24 to 36 Mc. Feeding the oscillator output into a 25 to 35 Mc bandpass filter and looking at the output of the filter with the spectrum analyzer, he saw

the third harmonics of the oscillator output. However, as the frequency was varied in the 8 Mc range and Mr. Wohlfort was observing the 24 Mc range of the output of the filter he also noticed a small output in the 32 Mc range. Since this smaller output varied in frequency directly with the oscillator frequency and because of its position in the frequency spectrum, he concluded it to be the fourth harmonic component of the fundamental frequency of the oscillator.

Mr. Wohlfort was able to reduce the fourth harmonic component, at a single frequency, to 1 per cent of the third harmonic amplitude. This he accomplished by making the half-period times of the output of the oscillator as symmetrical as possible. It was impossible for him to reduce the fourth harmonic to zero since the output could not be made symmetrical in all respects. And even the reduction to 1 per cent was a critical adjustment, as Mr. Wohlfort discovered, which did not hold for each frequency. Moreover, it was not a stable adjustment, drifting over relatively short periods of time.

As he reflected on the problem of eliminating the undesirable harmonics, Mr. Wohlfort concluded that he had four alternatives. He could continue working to cure the harmonics. He could completely redesign the circuit using a different approach, such as variable reactance instead of the switching technique which he had been working on. Or he could try further modification of the existing circuit to try to make it operate at 30 Mc. A final alternative, it seemed to him, would be to try for a design which would not reach the 30 Mc target but would operate around 20 Mc. He noted, however, that the laboratory equipment available for use in conjunction with the oscillator all operated around the 30 Mc range, so that to use an oscillator in the 20 Mc range it would be necessary to buy additional equipment. The minimum additional purchase, he expected, would be a new intermediate frequency amplifier costing around several hundred dollars.

Mr. Wohlfort had now been working on the circuit for two months, and there remained only two months to complete delivery of the oscillator on time. In view of the time constraint and alternatives before him, he wondered what his further course of action should be.

WILLIAM WOHLFORT (D)

Design of a Variable Frequency Oscillator

"Time became a major constraint on the oscillator design project as the end of the quarter approached," Mr. Wohlfort commented. "I was the only person working on the design, and my time in the laboratory was averaging between 25 and 30 hours per week. Exams were approaching, and I knew that studying would soon mean less time available for work on the project. Therefore, I concluded it would be impossible to follow more than one of the proposed alternative courses of action and still have an operating circuit in two months.

"There was no way I could see, short of complete redesign, for modifying the flip-flop circuit to meet the 25 to 35 Mc objective. A complete redesign, I thought, would most likely take more than two months -- probably something like three to four, when I considered my future working schedule. Using the third harmonic did give linear operation in the desired region. However, the instability of the circuit with time and its sensitivity to minor variations presented a real problem to reduction of the spurious fourth harmonic output. Possibly, I thought, complete isolation might reduce these effects, but I could see no guarantee of success. Furthermore, isolating the circuit could easily cost more than a new i-f amplifier, not to mention the resulting inconvenience in use and repairing. So, tentatively, I considered lowering the center frequency of the oscillator to a linear operating region -- below 20 Mc -- as the most desirable approach.

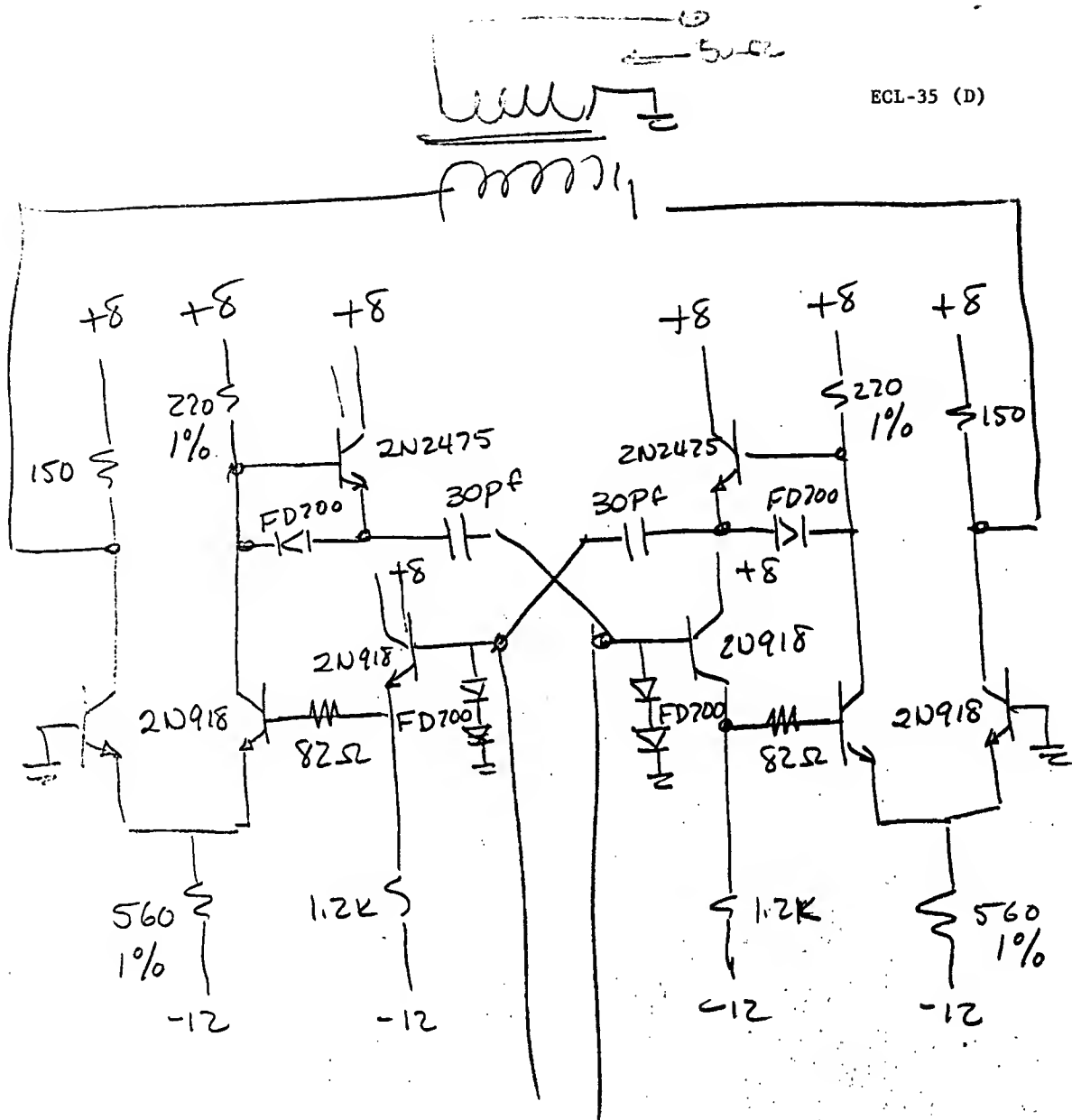
"I then met with Dr. May, Mr. Miller, and Mr. McCoy. Mr. McCoy thought that three to four months for redesign would be too long since he was almost at a point in his own work when he could begin to make use of an oscillator with a 10 Mc frequency range. Then, too, as I pointed out, there was no certainty that at the end of the three to four months, I would be successful in my redesign. Dr. May and Mr. Miller both agreed. In addition, they saw the fourth harmonic suppression effort as a big problem which, even though it might be solved initially, would most likely turn up again as components aged or even as components were replaced. This would mean that Mr. McCoy's tests might be suspect unless the oscillator were constantly monitored -- an approach which would tie up too much equipment and would unnecessarily encumber Mr. McCoy. The four men agreed, therefore, that the center frequency should be lowered to a point where a linear 10 Mc frequency range was possible.

"I showed Dr. May, Mr. Miller, and Mr. McCoy the data I had taken on linearity. It appeared that the circuit operated linearly below 20 Mc. It was decided then that the range would be from 10 to 20 Mc. This, they reasoned, would give the minimum percentage frequency range while still maintaining linearity. As I pointed out, the smaller the percentage frequency range, the less control current would have to vary. This then would make the current source design easier and, as I had shown earlier, tend toward more linear operation. Also, since even harmonics were known to be present in the oscillator output, as high an operating frequency consistent with linearity was necessary so that at the low oscillator frequency the second harmonic component would fall outside the bandpass of the rest of the test equipment.

"Since the circuit did not have to oscillate up to 30 to 40 Mc, I tried to optimize my design somewhat for 10 to 20 Mc operation. I increased the coupling capacitors from 15 pf to 30 pf to reduce the effects of stray capacitances while at the same time maintaining relatively small control currents (on the order of 2 to 4 ma). Mr. McCoy showed me an article in the November 23, 1964, edition of Electronic Design, "A Simple Way to Speed Multivibrator Recovery," pp. 52, 54, 55. The article described a method for speeding up the collector recovery time of a flip-flop circuit. Although I didn't think the circuit needed a faster recovery time, I added it anyhow. I thought that since I was only building one assembly, the additional cost was not important and that the recovery circuit could only guarantee wider operating limits. This in turn would enhance performance in the desired range. My final circuit is shown in Figure 1.

"After these optimizing modifications, I took data on the circuit operating between 10 to 20 Mc. The frequency vs. control current characteristic of the circuit is shown in Figure 2. Indeed, as I was pleased to notice, the circuit did operate linearly and, as I saw on the oscilloscope, at constant amplitude over the desired range."

ECL-35 (D)



To CURRENT SOURCE

FIG (1) - (D)

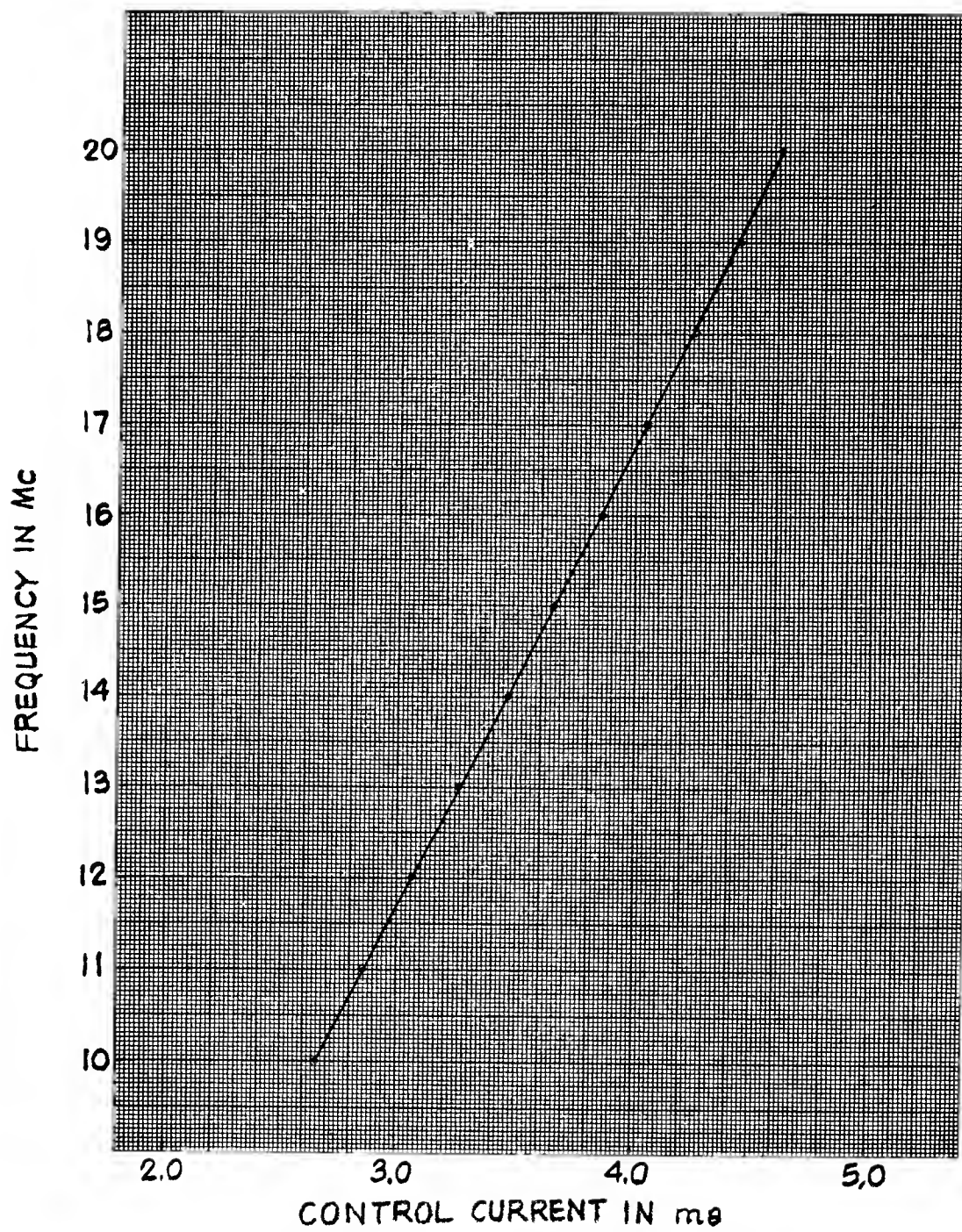


FIG. 2 - (D)
FREQUENCY VS CONTROL CURRENT
10Mc TO 20Mc